TECHNICAL NOTE R-161

AN ANNOTATED BIBLIOGRAPHY ON MOTION OF CHARGED PARTICLES IN MAGNETIC FIELDS AND MAGNETIC SHIELDING AGAINST SPACE RADIATION

By Perry F. McDonald

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AN ANNOTATED BIBLIOGRAPHY ON MOTION OF CHARGED PARTICLES IN MAGNETIC FIELDS AND MAGNETIC SHIELDING AGAINST SPACE RADIATION

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ABSTRACT

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This annotated bibliography on the theory of charged particle motion in magnetic fields and the shielding against charged particle radiation using magnetic fields is divided into five sections: 1) general references on charged particle motion and cosmic rays, 2) motion of untrapped particles in magnetic fields, 3) motion of trapped particles in magnetic fields, 4) ring currents in the magnetosphere and 5) space radiation shielding using magnetic and electric fields. It should be helpful to those interested in the interaction of cosmic rays and energetic solar particles with the geomagnetic field and those interested in the active methods of shielding against space radiation.

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INTRODUCTION

This bibliography was compiled with emphasis on the theoretical aspects of charged particle motion in magnetic and electric fields. Particles and fields research has abounded in recent years, and the rate of production of literature in this area is very high at present. Since much of the literature pertains to experimental measurement of distributions of high energy particles, only survey articles on this type of literature are listed. The motivation for the assembly of this bibliography is the possibility of using magnetic fields to shield space vehicles from charged particle radiation. The similarity of this problem to the interaction of cosmic rays with the geomagnetic field makes much of the research on the cosmic ray problem applicable. Due to the slightly narrowed field of interest, it will be necessary for the reader to consult some of the general references, survey articles and the bibliography (Hess, et. al., 1965) listed in order to obtain a comprehensive listing of all the literature pertaining to particles and fields research. An effort has been made to indicate those items which have good lists of references.

The bibliography is divided into five sections:

- General references on charged particle motion and cosmic rays
- Motion of untrapped particles in magnetic fields
- Motion of trapped particles in magnetic fields
- Ring currents in the magnetosphere
- Space radiation shielding using magnetic and electric fields.

Within each section the references are arranged alphabetically by first author. In a few cases the decision as to which section an article was to be assigned was somewhat arbitrary and it may be necessary to look in more than one section for a given article since there are no duplications.

Abstracts by the authors are included if they were available. In other cases the reviewer has attempted to describe the contents of the reference and these descriptions may include statements from the texts of the references.

GENERAL REFERENCES ON CHARGED PARTICLE MOTION AND COSMIC RAY INTERACTIONS

Alfvén, H. and C. G. Fälthammar, Cosmical Electrodynamics, Oxford University Press, London, 228 pp., 1963

The general motion of charged particles in homogeneous and non-homogeneous magnetic fields with and without electric fields is treated in some detail. Slowly varying magnetic fields are considered and the adiabatic invariants are discussed. Motion in the dipole field is discussed using Störmer's method and the perturbation method. The fundamental principles of magnetohydrodynamics, plasmas, and magnetic plasma are discussed.

Chamberlain, J. W., Motion of Charged Particles in the Earth's Magnetic Field, Gordon and Breach, New York, 1964

The author has given a brief introduction to one area of plasma physics directed primarily to geophysicists. He has dealt mainly with the orbit theory of particles in a magnetic field with particular emphasis on the geomagnetic field. He gives a discussion of particle motion in a dipole field including a review of Störmer's theory and the forbidden regions derived therefrom. A chapter is devoted to the Guiding-Center theory of particle orbits where the adiabatic invariants of the motion of charged particles in the geomagnetic field are discussed.

Hess, W. N., G. D. Mead and M. P. Nakada, "Bibliography of Particles and Fields Research," NASA TMX 55192, 89 p., January, 1965

This bibliography is intended to be a comprehensive list of all published scientific papers on particles and fields research beginning in 1957. It is organized into nine subject categories: the solar wind and its effects on the earth, radiation belts, artificial radiation belts, aurora, solar energetic particles, Galactic Cosmic rays, geomagnetism, neutrons and general references.

Johnson, T. H., "Cosmic-Ray Intensity and Geomagnetic Effects", Revs. Mod. Phys. 10, 1938

This paper presents a review of the knowledge on cosmic rays to that date and gives a comprehensive bibliography of the literature. Under the theory of geomagnetic effects, Störmer's theory of excluded regions, the Lemaitre-Vallarta theory of the allowed cone, the geographical distribution of cosmic ray intensity and correlation of geomagnetic cosmic-ray effects are discussed.

Lehnert, Bo, Dynamics of Charged Particles, North Holland Publishing Company, Amsterdam and Interscience Publishers, New York, 1964

The dynamics of ionized matter in electric and magnetic fields are presented mainly on basis of a single particle picture. The basic equations governing the motion of charged particles in electric and magnetic fields are discussed in detail. A chapter is devoted to orbit theory including first order and higher order approximations and the guiding center approximation. A chapter is devoted to the adiabatic invariants of the motion of trapped particles. The radiation of charged particles moving in magnetic fields is also discussed.

Sandström, A. E., Cosmic Ray Physics, North Holland Publishing Company, Amsterdam, John Wiley & Sons, New York; 421 p., 1965

A good general survey of the whole field of cosmic rays is given. Of particular interest is the chapter on cosmic rays and the earth's magnetic field. In this chapter, the Störmer's theory, Liouville's theorem, the east-west asymmetry and azimuthal effect, the longitudinal effect, threshold rigidities and asymptotic directions in a dipole field are discussed. Another chapter is concerned with the radiation belts and the motion of trapped particles.

Spitzer, Lyman, Jr., Physics of Fully Ionized Gases, Interscience Publishers, Inc., New York, 1956

The first chapter deals with the fundamentals of charged motion in various combinations of electric and magnetic fields. The remaining chapters are concerned with a macroscopic description of the behavior of a fully ionized gas.

Störmer, Carl, The Polar Aurora, Oxford University Press, London, 1955

In addition to a vivid and comprehensive discussion of the aurora, the author gives a rather detailed discussion of the dynamics of charged particles in magnetic dipole fields. The pioneering work by Störmer in this field is summarized. The differential equations of motion are analyzed and the constants of motion are found. The allowed and forbidden regions are discussed and the results of numerical integration of numerous particle trajectories are presented.

MOTION OF UNTRAPPED PARTICLES IN MAGNETIC FIELDS

Alpher, R. A., "Theoretical Geomagnetic Effects in Cosmic Radiation," Jour. Geophys. Res. 55, No. 4, p. 437, 1950

A brief review is given of the theory of the effect of the earth's magnetic field on cosmic radiation. The basic results of the theory are presented in graphical form and are intended to be useful in the experimental investigation of cosmic radiation. The material presented includes curves of minimum energy of arrival, as measured in Störmer units, *versus* azimuth angle, for zenith angles at 10° intervals, arising from the combined Störmer and shadow cone (for all latitudes at 10° intervals), and from the main cone (at latitudes 0°, 20°, and 30°). Minimum momentum in BeV/c and minimum energy in BeV for protons and heavy nuclei are given *versus* geomagnetic latitude for azimuths N, S, E, and W, at all zenith angles in 15° steps. Other available presentations of the basic theory are mentioned and the conversion procedures involved in the application of the theory are described. (Author)

Bland, C. J., "A Laboratory Scale Model for the Investigation of Cosmic Ray Threshold Rigidities," Phil. Mag. 7, 8th Series, p. 1487 - 1501, 1962

A technique is described for the study of the geomagnetic threshold rigidities by means of a laboratory scale model in which the motion of the cosmic ray particles in the earth's magnetic field is simulated by that of a beam of electrons moving in the magnetic field of a terrella, scaled so as to represent the geomagnetic field. Störmer and main cone threshold rigidities have been detected by this technique both for the dipole representation of the geomagnetic field and for a field including non-dipole terms roughly similar in magnitude to those occurring in the earth's field. The modifications to the Störmer threshold rigidities, calculated by the Quenby-Webber method for the terrella field, have been checked and a preliminary investigation of the effect on the threshold rigidities of uniform fields has been carried out. (Author)

Fermi, E., Nuclear Physics, University of Chicago Press, Chicago, pp. 224 - 234, 1950

The motion of charged particles in the earth's magnetic field is discussed in detail assuming that the earth's field is that of an off-centered dipole. The Lagrangian equations of motion in spherical coordinates are used to derive the Störmer integral. The allowed and forbidden regions are discussed; the Störmer cone and the shadow effect of the earth are explained. The application of Liouville's theorem to the calculation of cosmic ray intensities is reviewed.

Firor, John, "Cosmic Radiation Intensity-Time Variations and Their Origin. IV. Increases Associated With Solar Flares," Phys. Rev. 94, No. 4, p. 1017, 1954

The distribution on the earth of the impact points for particles of magnetic rigidities 1 to 10 Bv, which originally approach the earth from the direction of the sun, is derived, using principally the published results of numerical integrations of cosmic-ray orbits and model experiments on the motion of charged particles in a dipole magnetic field. Three impact zones for such particles are discussed. Two of these zones include only a small range of local times and, for the special case of the sun in the plane of the geomagnetic equator, are centered near 4 a.m. and 9 a.m. The third zone has no strong local time dependence. Assuming the source of charged particles to subtend a finite angle at the earth, the relative counting rates for detectors in the three zones are estimated. The counting rate due to particles from the sun is expected to be three to seven times larger in the morning zones than in the background, or nonlocal-time dependent, zone. The morning impact zones are shown to have a seasonal motion of several hours in local time.

Reports of observations made during four large increases of cosmic-ray intensity at the times of solar flares are compared with the distribution predicted for particles from the sun. The observed increases agree with the predicted distribution and counting rate except at very high latitudes on the earth. A possible reason for this discrepancy is suggested. (Author)

Gall, Ruth, "Penetration Through the Magnetopause and Trapping in Its Vicinity," Jour. Geophys. Res. 69, No. 19, p. 4157 - 4161, 1964

The Störmer theory of allowed and forbidden regions is applied to the geomagnetic dipole field which is confined to the magnetosphere by the solar plasma. Injection and trapping of cosmic rays and solar protons into the distorted field are considered.

Hunter, R. A., "On the Penumbra of Cosmic Radiation," Phys. Rev. 55, pp. 15 - 23, 1939

The development of the theory of the penumbra is given, and a few examples of penumbral trajectories are shown. Pairs of values of the energy and latitude having penumbral regions are indicated. Two methods of analyzing the data obtained by means of Bush's Differential Analyzer are given: the first yielding the allowed directions for just one type of penumbral orbit over all latitudes and for one energy; the second giving the whole penumbra for one energy and one latitude. The energy chosen in each case was r = 0.425 Störmer (1.08×10^{10} ev for electrons). By means of the second method, the almost complete allowed cone is obtained for this energy and for a geomagnetic latitude of 20°. (Author)

Jory, F. S., "Influence of Geomagnetic Quadrupole Fields Upon Cosmic-Ray Intensity," Phys. Rev. 102, No. 4, pp. 1167 - 1173, 1956

The effect upon cosmic-ray particles of the quadrupole part of the earth's magnetic field has been calculated, using the results of the magnetic survey of 1945. The effect predicted from the zonal quadrupole term is a northern shift of the cosmic-ray latitude curve. The 1945 magnetic center was calculated, using Schmidt's method, and it is 0.0629 earth radii from the center of the earth as compared to 0.0536 earth radii in 1922. The shift in magnetic center results in an increase in the predicted longitude effect. The residual or sectorial quadrupole effect upon cosmic-ray intensity is predicted to be a two-period sine curve in the longitude effect. (Author)

Jory, F. S., "Selected Cosmic-Ray Orbits in the Earth's Magnetic Field," Phys. Rev. 103, No. 4, pp. 1065 - 1075, 1956

A set of 663 charged-particle orbits in the earth's dipole magnetic field has been obtained by integration, using the AVIDAC computer of the Argonne National Laboratory. The orbits integrated were selected according to their usefulness in the analysis of cosmic-ray intensity increases associated with solar flares. The calculation of intensity increases for different locations on the earth is discussed using the orbit results. (Author)

Kasper, J. E., "The Earth's Simple Shadow Effect on Cosmic Radiation," Suppl. Nuovo Cimento XI, Series X, No. 1, 1959

This paper describes a new investigation of the earth's simple shadow effect on cosmic radiation. It is shown that previously published simple shadow cones are in error. The new shadow cones are obtained by numerically integrating the equations of motion for a large number of charged particle trajectories on a high speed computer.

Kasper, J. E., "Geomagnetic Effects on Cosmic Radiation For Observation Points Above the Earth," Jour. Geophys. Res. 65, No. 1, pp. 39 - 53, 1960

The theory of geomagnetic effects on cosmic radiation is discussed for the case in which the point of observation is above the surface of the earth. Parts of the older geomagnetic theory are readily modifiable for application under the new conditions; the manner in which ordinary Störmer theory and the Lemaitre-Vallarta theory of the main cone can be adapted is discussed. However, the simple shadow cones of Schremp appear now in a new light; as the point of observation rises from the earth, the simple shadow effect which exists at the earth makes a smooth transition to a new kind of earth's shadow effect. Associated with this effect are

principal shadow cones which are defined by reference to the properties of certain families of trajectories. For observation points above the earth, a modification in our view of the penumbral region is required; this is discussed very briefly. Extensive computation of principal shadow cones have been carried out by machine integration of the equations of motion and subsequent abstraction of data from these trajectories. Sample computed cones are given for representative particle rigidities, geomagnetic latitudes, and altitudes of observation. The centered dipole approximation for the magnetic field of the earth is used throughout. (Author)

Kellogg, P. J., "Calculations of Cosmic-Ray Trajectories Near the Equator," Jour. Geophys. Res. 65, No. 9 pp. 2701 - 2703, 1960

New calculations of cutoff rigidities near the equator have been carried out on a fast electronic computer, using the 48-parameter expression for the earth's magnetic field. The results are in good accord with observations. (Author)

Kelsall, Thomas, "Solar Proton Impact Zones," Jour. Geophys. Res. 66, No. 12, pp. 4047 - 4070, 15 refs., 1961

The trajectories of charged particles moving in a magnetic dipole field have been calculated by numerical integration for application to data on the intensity variation of cosmic rays during recent solar events. All seasons and times of day have been covered by assuming a range of orientations of the incident particle beam with respect to the magnetic dipole axis. The points of impact with the earth have been determined for protons with energies from 0.05 to 50 BeV. The computation includes 4000 trajectories and fills several gaps in previous investigations. In agreement with earlier calculations, the results indicate that the protons strike in well-defined areas between 0 and 1200 hours local time and are focused into small areas of impact at low energies. The investigation has revealed two points that are not new but have received relatively little attention in earlier work. First, the relative number of impacts in the northern and southern geomagnetic hemispheres is strongly dependent on season. Second, under certain conditions of season there is a class of trajectories, which may be called quasi-trapped, constituting a set of paths resembling the trapped trajectories first discovered by Störmer but connected to infinity. It is suggested that injection into trapped orbits from these quasi-trapped trajectories may make a contribution to the population of the Van Allen belts. (Author)

Koenig, H. P., "The Solid Angle Subtended By the Main and Shadow Cones of Cosmic Radiation," Phys. Rev. 58, No. 5, pp. 385 - 386, 1940

For the calculation of the longitude and latitude effects, as well as the time variations, of charged primary cosmic radiation, the

knowledge of the solid angle subtended by the main and shadow cones for all latitudes and energies is essential. This solid angle is calculated over a wide range of energy and latitude from the results of Lemaitre and Vallarta, and from those of Schremp, and the results given in the form of several graphs.

Lemaitre, G. and M. S. Vallarta, "On Compton's Latitude Effect of Cosmic Radiation," Phys. Rev. 43, No. 2, pp. 87 - 91, 1933

By considering the influence of the earth's magnetic field on the motion of charged particles (electrons, protons, etc.) coming to the earth from all directions in space, it is shown that the experimental variation of cosmic-ray intensity with magnetic latitude, as found by Compton and his collaborators, is fully accounted for. The cosmic radiation must contain charged particles of energy between limits given in the paper. For predominantly negative particles, there must be in the region of rapidly varying intensity a predominant amount of rays coming from the east and conversely for positive rays. Because of the fact that in regions near the magnetic equator there is a predominance of rays coming nearly horizontally, the absorption by the atmosphere may be increased. (Author)

Lemaitre, G. and M. S. Vallarta, "On the Geomagnetic Analysis of Cosmic Radiation," Phys. Rev. 49, pp. 719 - 726, 1936

The results of an extensive study of trajectories asymptotic to a certain family of periodic orbits in the earth's magnetic field, carried out by means of Bush's differential analyzer, are presented in this paper. The theory of the region of full light, or main cone, is fully discussed. Attention is then restricted to the section of the main cone in the plane of the geomagnetic meridian and it is shown that the north-south asymmetry furnishes the most direct approach to the analysis of the energy spectrum in a wide region, independently of the particles' sign. Further, it is shown that the general shape and the minimum of the north-south asymmetry discovered by Johnson in the course of his Mexican experiments are fully accounted for by the action of the earth's field. (Author)

Lemaitre, G. and M. S. Vallarta, "On the Allowed Cone of Cosmic Radiation," Phys. Rev. 50, No. 6, pp. 493 - 504, 15 refs. 1936

Further results of an extensive study of trajectories asymptotic to a known family of unstable periodic orbits in the earth's dipolar magnetic field, carried out by means of Bush's differential analyzer, are presented in this paper. A detailed discussion is given of our methods of determining asymptotic trajectories by means of the differential analyzer and by numerical integration of a whole family at a time; comparison of the results obtained shows the absence of systematic errors

of any consequence in the mechanical integrations and exhibits the precision attained with the differential analyzer. The families of asymptotic trajectories are then analyzed systematically in order to determine the main cones for latitudes up to 30°. This leads to the theory of the azimuthal effect and a study of the region in the vicinity of the zenith. (Author)

Lüst, R., "Impact Zones For Solar Cosmic-Ray Particles," Phys. Rev. 105, No. 6, pp. 1827 - 1839, 1957

Orbits for cosmic-ray particles starting from the vicinity of the sun and passing through the geomagnetic dipole field were integrated by using the AVIDAC computer at the Argonne National Laboratory. The methods for integration used in Chicago and Göttingen were compared. Counting rates at the top of the atmosphere were calculated from the integrated orbits in order to make possible the analysis of cosmic-ray intensity increases during solar flares. Different source widths and declinations were assumed. The calculated counting rates are based on a flat rigidity spectrum at the source. This investigation shows that: a) distinctive impact zones exist even for large source widths; b) the position of these zones and the counting rates within these zones depend strongly upon the declination of the source; c) the earth's magnetic field produces a focusing effect especially at higher latitudes. (Author)

Mac Leod, M. A. and R. W. Waniek, "Injection of High Velocity Charged Particles into Strong Magnetic Fields," Jour. Applied Phys. 34, No. 5, pp. 1415 - 1423, 1963

A general formulation of the axially symmetric, magnetostatic field, forbidden-zone theory is given and the useful concept of the paraxial forbidden zones is introduced. This theory is then applied to obtain qualitative answers to the injection problem for the bell-shaped field for both zero and non-zero values of the angular momentum constant. Quantitative relations for the zero angular momentum constant case are obtained using the bell-shaped field paraxial trajectories. A discussion of the limitations of the approximations employed is included. (Author)

Prescott, A. D., "Distribution of Unbound Charged Particles in the Static Magnetic Field of a Dipole," NASA TMX-51312, N64-17685, 78 p., 24 refs., 1964

The distribution of relativistic unbound charged particles in the static magnetic field of a dipole with respect to a monoenergetic, isotropic, time independent homogeneous distribution at infinity is determined by assuming Liouville's theorem and the Störmer theory of allowed and forbidden regions for unbound particle motion. For an

isotropic distribution, the allowed solid angle for particle motion at any given point (r, θ, ϕ) in the field is determined by mapping point (r, θ, ϕ) into the allowed and forbidden regions of Störmer space, via the Störmer transformation, at a particular particle impact parameter. The totally and partially shielded regions are defined and are examined with particular emphasis on the shielding effectiveness of the partially shielded region to charged particles. The volumes of the totally and partially shielded regions are numerically computed. Once the totally and partially shielded regions are established, the momentum cutout in momentum space at point (r, θ, ϕ) is determined by mapping the point into the totally, partially, and unshielded regions in Störmer space with particle momentum as a variable. These methods are then used to compute the proton flux ratio at points on the surface of a spherical spaceship as a function of particle kinetic energy. The theory is applied to the dipole field of a finite current loop and a study of the totally and partially shielded regions shows that the partially shielded region provides protection in the high energy regime where the totally shielded region is effectively nonexistent. (Author)

Prescott, A. D., "Some Fundamental Characteristics of Charged Particle Motion in Axially Symmetric Multipole Fields," MSFC, R-RP-INN-65-1, February, 1965

A new method of determining the points in phase space where two isolated regions of permissible charged particle motion connect at a saddle point is developed after showing where and why saddle points can exist in any axially symmetric infinitesimal magnetic field. The method is applied to any axially symmetric infinitesimal multipole field and then to any general axially symmetric magnetic field yielding conditions on the field components which must be satisfied at each saddle point. The magnetic field components are uniquely defined at each saddle point in any general axially symmetric magnetic field, and an empirical method of finding saddle points by examining contour maps of the magnetic field components is presented. The magnetic field is shown to be parallel to the magnetic moment axis at each saddle point leading to the existence of a circular bound orbit at each saddle point in any general axially symmetric field.

The number of saddle points, their coordinates, and symmetric properties of charged particle motion in the axially symmetric infinitesimal multipole fields are presented and discussed. The sufficiency condition for the existence of a saddle point is critically examined, and it is shown that in any axially symmetric infinitesimal multipole field the necessary condition is both necessary and sufficient. (Author)

Quenby, J. J. and W. R. Webber, "Cosmic Ray Cut-Off Rigidities and the Earth's Magnetic Field," Phil. Mag. 4, 8th Series, pp. 90 - 113, 1959

Approximate values of the vertical cut-off rigidities for cosmic ray particles in the earth's magnetic field have been deduced taking into account both dipole and non-dipole parts of the internal field. The vertical cut-off rigidity for a dipole field at latitude λ is given by $P = (M/4r_e^2) \cos^4 \lambda$ where M is the dipole moment and r_e is the radius of the earth. Corrections are added to this expression for the non-dipole parts of the field of the earth. The accuracy of the calculated values is discussed and it is shown that they fit the experimental data rather well.

Quenby, J. J. and G. J. Wenk, "Cosmic Ray Threshold Rigidities and the Earth's Magnetic Field," Phil. Mag. 7, pp. 1457 - 1471, 1962

Approximate corrections to the vertical threshold rigidities for cosmic rays in the earth's magnetic field are given which take into account both the effects of the non-dipole part of the internal field and the penumbra. The thresholds are tabulated every 2 1/2° geographic latitude and every 5° geographic longitude. The accuracy of these thresholds is discussed and it is shown that they fit experimental data better than do the approximations of Quenby and Webber, 1959.

Ray, E. C. and J. E. Kasper, "Some Theorems Concerning the Motion of an Electrically Charged Particle in a Dipole Magnetic Field," Annals Phys. 20, pp. 119 - 131, 1962

We prove various theorems related to the application to cosmic rays of the theory of the motion of an electrically charged particle in a dipole magnetic field. The theorems are essentially those conjectured by Schremp. In making the proofs, we assume that the so-called trajectories of the first and second kinds have certain properties in the large. These properties can be verified numerically and by series expansions in any particular case. (Author)

Ray, E. C., "Theorems Concerning the Allowed Cone of Cosmic Radiation," Goddard Space Flight Center (X63-12333), 1963

A previous investigation of the cosmic ray shadow cone and low latitude main cone is extended to include the main cone at all higher latitudes. The results are embodied in two theorems which specify the nature of a boundary of a class of trajectories, none of which are forbidden. No numerical results are included. (Author)

Ray, E. C., "On the Motion of Charged Particles in the Geomagnetic Field," Annals Phys. 24, pp. 1 - 18, 1963

We construct an approximate first integral of the equations of motion of a charged particle in a static magnetic field. The integral is analogous to the Störmer integral, but it is not required that the field have axial symmetry in order for the integral to be exact. The integral reduces to that of Störmer when the field does possess axial symmetry. It is used to obtain results concerning trapped particles and cosmic rays previously derived by various people using a variety of techniques. The new technique can readily be extended to cover situations not previously tractable. (Author)

Ray, E. C., "Cosmic-Ray Cutoffs at High Latitude," Jour. Geophys. Res. 69, No. 9, pp. 1737 - 1741, 1964

The measurements of many spectrums of solar protons at northern latitudes have shown that the cutoffs are commonly much lower than those calculated for the earth's magnetic field as deduced from surface measurements, together with any reasonable ring current. We show that most of the observations can be reasonably accounted for with a magnetic field which, in addition to the contributions mentioned, has a turbulent component everywhere beyond a certain distance from the center of the earth. The model is essentially that explored by Parker and by Rothwell. The fact that the solar wind distorts the field at great distances must, as Akasofu et al. suggested, produce a modification, the nature of which is a reduction of the cutoff rigidity. (Author)

Razdan, H. and A. L. Summers, "Asymptotic Cones of Acceptance of Cosmic Ray Neutron Monitors in a Geomagnetic Field Distorted By the Solar Wind," NASA TMX-51943, 1964

The asymptotic cone is defined as the solid angle containing the asymptotic directions of approach of cosmic ray particles outside the influence of the geomagnetic field that significantly contribute to the counting of a ground detector. The cones were obtained by numerically integrating cosmic ray trajectories for a distorted geomagnetic field. The distorted field assumed was that created by a combination of the geomagnetic dipole and an image dipole of moment 28 times that of the earth's equivalent dipole placed at a distance 28 earth radii along the noon meridian. The asymptotic cones for the distorted field were compared with those for a dipole field.

Sauer, Herbert H., "A New Method of Computing Cosmic-Ray Cutoff Rigidity For Several Geomagnetic Field Models," Jour. Geophys. Res. 68, No. 4, pp. 957 - 971, 1963

An approximate method of computing cosmic-ray cutoff rigidities is presented. The method consists of integrating the equations of motion for

a particle of given rigidity and direction of arrival in the real field to determine the corresponding position and direction of the particle at the transition radius where the Störmer theory can be invoked to determine whether the particle can have arrived from infinity. The procedure is followed for a sequence of rigidities until the minimum rigidity that the Störmer criterion allows is reached. The geomagnetic field is represented by the combination of a sixth order magnetic field whose origin lies entirely within the earth and that due to a filamentary equatorial ring currents of various radii and magnetic moments. The sixth order spherical harmonic expansion of the scalar magnetic potential is that obtained by Finch and Leaton. Vertical cutoff rigidities have been computed for a large number of stations for latitudes greater than ±45°. (Author)

Sauer, H. H. and E. C. Ray, "On Cosmic Ray Cut-Offs," State University of Iowa SUI-63-8, March, 1963

A cosmic ray cut-off in the Störmer sense is defined for sufficiently high latitudes when the magnetic field, while not axially symmetric, becomes approximately so at sufficiently great distances from the earth. It is shown that the cut-off, when so defined, is given by a simple function of McIlwain's L parameter. Numerical comparisons are made with a previous computer study of cut-offs defined in the same way. The expression for cut-off in terms of L suggests that the cut-off in the direction of the magnetic field should be approximately constant along a line of force. This is shown numerically to be so at latitudes too low for the derivation of the L expression to hold, for a particular field model. (Author)

Schremp, E. J., "I. General Theory of the Earth's Shadow Effect of Cosmic Radiation," Phys. Rev. 54, pp. 153 - 157, 1938

An inquiry is made into the fundamental mode of origin of the allowed cone of cosmic radiation introduced by Lemaitre and Vallarta. Two kinds of allowed cone are distinguished. One of these, that discussed by Lemaitre and Vallarta, postulates the presence of an impenetrable earth; for it all forbidden directions are due to the earth's shadow effect. The second type of allowed cone, applicable in the first approximation to such problems as that of the sun's magnetic field, does not postulate the presence of an impenetrable earth; for it all forbidden directions are associated with bounded charged particle orbits. The general topological features of each of these kinds of allowed cone, and their relationship to one another, are described. (Author)

Schremp, E. J., "II. The Simple Shadow Cone of Cosmic Radiation," Phys. Rev. 54, pp. 158 - 162, 1938

The present paper is a brief summary of the results obtained from a study, by means of Bush's differential analyzer, of those trajectories of a charged particle in the field of a magnetic dipole which determine the simple shadow cone for all latitudes and energies. (Author)

Schwartz, M., "Penumbra and Simple Shadow Cone of Cosmic Radiation," Suppl. Nuovo Cimento XI, Series X, p. 27, 1959

The main cones consist only of trajectories arriving unobstructed at the earth having come directly from infinity without making loops representing turning away and turning towards the dipole. For each point on the earth, the region between the main cone and the Störmer cone consists of alternating bands of allowed and forbidden trajectories which respectively either arrive at the earth from infinity or do not. This region is called the penumbra. This paper extends the investigation of the main cone and the penumbra to higher latitudes than previously reported. The results were obtained from trajectory calculations made by the high speed computer, AVIDAC. Vertical direction results are used to fit total vertical intensity data, thereby determining an integral rigidity spectrum and at the same time defining effective rigidity cut-offs.

Stern, David, "The Vector Potential and Motion of Charged Particles in Axisymmetric Magnetic Fields," Jour. Geophys. Res. 69, No. 13, pp. 2715 - 2719, 1964

From the conventional expansion of a scalar magnetic potential (such as the earth's), an expansion of the vector potential is obtained. This expansion is used for analyzing the motion of charged particles in axisymmetric magnetic fields, with special attention to such fields that do not deviate far from a dipole. The results are compared with those of Quenby and Webber. Finally, the relation between Störmer's first integral and the third adiabatic invariant is traced. (Author)

Stern, David, "The Cosmic Ray Anisotropy," Platet. Space Sci. 12, pp. 973 - 978, 1964

Three different explanations for the observed cosmic ray anisotropy are investigated. The possibility that the anisotropy is due to the existence of trapped orbits in the interplanetary field is explored by analysing the motion of charged particles in a stretched dipole field. It is found that an anisotropy is possible, but only when several unlikely conditions are met. Two other theories of the anisotropy, ascribing it either to a sunward flux density gradient or to the

Compton-Getting effect, are then discussed. It is shown that in general both effects occur together; for conservative fields they cancel each other and no anisotropy occurs, as might indeed be expected from Liouville's theorem. Consequently, any gradient of cosmic ray flux density which may be observed in interplanetary space is not necessarily connected with the observed anisotropy. (Author)

Stetson, R. F., B. N. A. Lamborn and D. L. Lafferty, "Investigation of Electron Trajectories in an Axially Symmetric Magnetic Field," Jour. Appl. Phys. 34, No. 3, pp. 516 - 519, 1963

The experimental behavior of electron beams of variable energies injected into an axially symmetric magnetic field which varies as 1/r is investigated. When the injection velocity is less than that required for circular motion, the beam spirals in toward an inner radius and reverses direction. The particle orbits are in agreement with those obtained from the equation of motion of a single charged particle injected into such a field. (Author)

Störmer, Carl, "Critical Remarks on a Paper by G. Lemaitre and M. S. Vallarta on Cosmic Radiation," Phys. Rev. 45, pp. 835 - 838, 1933

Störmer corrects and puts into historical perspective the paper of the cited authors which is found in Phys. Rev. 43, p. 87, 1933.

Swann, W. F. G., "Application of Liouville's Theorem to Electron Orbits in the Earth's Magnetic Field," Phys. Rev. 44, pp. 224 - 227, 1933

It is pointed out that in the application of Liouville's theorem to the problem of cosmic-ray intensities, Lemaitre and Vallarta have implicitly taken the electron momentum as that corresponding to a free particle. Calling this momentum p' the particle momentum, we have to realize that Liouville's theorem is usually based upon the Hamiltonian equations in which the momentum p associated with an electron is not the same as p', but is connected with it by the relation $p = p' + eU/c$, where U is the vector potential determining the magnetic field. The Hamiltonian equations are not valid in terms of momenta of the type p', and it is not therefore clear that Liouville's theorem is valid when expressed in terms of these momenta. The object of the paper is to show that a theorem the equivalent of Liouville's theorem is, in fact, true in terms of the coordinates and the momenta p', so that the ultimate validity of the use of the theorem by Lemaitre and Vallarta is substantiated. It is to be observed, moreover, that the validity of this extended form of Liouville's theorem is true even in the presence of an electric field. (Author)

Urban, E. W., "Critical Störmer Conditions in Quadrupole and Double Ring Current Fields," to be published, Jour. Math. Phys., January-February, 1966

A theoretical study has been made of the behavior of the critical Störmer pass points for general axially symmetric magnetic configurations. A topological method has been derived to predict the occurrence of the critical Störmer conditions for charged particle exclusion. This analytic technique, when applied to geomagnetically interesting fields, should be a useful aid to the understanding of experimental data. The method is applied here to three magnetic geometries: double ring currents with parallel dipole moments and with antiparallel dipole moments and the axial magnetic quadrupole. The topology of the regions representing allowed motion is treated systematically, and the behavior of the critical pass points is illustrated in typical Störmer plots. For the quadrupole and the antiparallel ring system, critical pass points are found to occur only out of the equatorial plane. For the parallel ring system, critical points can occur in or out of the equatorial plane. For certain special conditions, as many as three simultaneous critical pass points are found, and two simultaneous points occur for a wide range of parameters. (Author)

Vallarta, M. S., "Theory of the Geomagnetic Effects of Cosmic Radiation," Handbuch der Physik, Bd XLVI, Springer-Verlag, Berlin, 1961

The Störmer theory of the motion of charged particles in the geomagnetic field is reviewed and extended to more exact solutions. The allowed directions of arrival at any point on the earth, for particles of any given energy, fill up a cone of many sheets, generally of very complicated shape. This cone has been called by Lemaitre and Vallarta the allowed cone. The allowed cone in general consists of three regions: first, there is the main cone, within which all directions are allowed; surrounding the main cone there is a second region in which certain bands or patches of directions are allowed and the rest forbidden, which has been named the penumbra; lastly, there is a region, the shadow cone, outside of which all directions are excluded. An absolute limit for all allowed directions is the Störmer cone which has the property that outside it the region of space containing the earth and that containing all trajectories coming from outside the earth are disconnected. The Störmer cone is a right circular cone with its vertex at the observer and axis along the east-west line. The penumbra lies in general between the main cone and the shadow cone. As a rule, it does not reach the Störmer cone, which is only exceptionally touched by the main cone. The Liouville theorem applied to a particle distribution which is isotropic at infinity allows one to calculate the intensity at a given point on earth by finding the allowed cone and multiplying the subtended solid angle and multiplying it by the intensity in any allowed direction for any given energy.

Webber, W. R., "The Motion of Low-Rigidity Cosmic Rays in the Earth's Magnetic Field and the Effects of External Fields," Jour. Geophys. Res. 68, No. 10, pp. 3065 - 3085, 43 refs. 1963

A general approach is made to the discussion of motion of low-rigidity cosmic rays in a dipole field; it rests on the characteristics of the motion of these particles in the Alfvén regime and a family of trajectories passing near the origin of the dipole itself, called nullbahnen, first calculated by Störmer. The general rigidity range of applicability of the method is discussed. It is found that within this range of applicability the asymptotic directions of the particles outside the earth field may be determined for a wide range of arrival latitudes and arrival directions with respect to the vertical without resorting to the numerical integration of trajectories. The presentation is extended to the earth's real field; asymptotic directions applicable to certain locations are presented and discussed for solar-flare particles and galactic variations detected by neutron monitors as well as lower-rigidity particles detectable only at balloon and satellite altitudes. Finally, the effects of external fields on the asymptotic directions are discussed, and the asymptotic directions appropriate to the arrival of solar-flare particles as detected by neutron monitors at sea level in the presence of ring currents are presented. (Author)

MOTION OF TRAPPED PARTICLES IN MAGNETIC FIELDS

Avrett, E. H., "Particle Motion in the Equatorial Plane of a Dipole Magnetic Field," Jour. Geophys. Res. 67, No. 1, p. 53 - 58, 1962

An exact relation is derived which describes bound particle orbits in the equatorial plane of a dipole magnetic field. An exact expression is then obtained for the average angular velocity of the particle about the dipole axis. The corresponding drift velocity is compared with the usual first-order expression based on a constant local field gradient. It is shown that the first-order expression for the drift velocity can be considerably in error when the particle loops are not small compared with the mean distance from the dipole axis. (Author)

Baker, M. B., "Geomagnetically Trapped Radiation," Douglas Aircraft Company, Report SM-47635, October, 1965

This report provides a comprehensive description of the trapped charged particle environment which can be used to find the radiation doses to which a vehicle will be exposed. The first and second sections contain a description of the trapped radiation environment, including a discussion of the source and loss mechanisms and the dynamics of the particle motions, a description of source of the data and the compilation techniques, and graphic displays of the fluxes. The third section is a description of a satellite flux computer program and the fourth section presents the integrated fluxes and spectra produced by the computer for sample trajectories.

Christofilos, N. C., "Trapping and Lifetime of Charged Particles in the Geomagnetic Field," Radiation Laboratory, University of California, UCRL-5407, N63-83870, 12 pp., 1958

Trapping of charged particles, especially fast electrons, within the geomagnetic field has been examined. Since the lines of the geomagnetic field converge towards the earth, they act as magnetic mirrors in which fast electrons can oscillate back and forth. If the reflection points are in the upper atmosphere, the electrons are scattered by the air molecules. Since the atmospheric density decreases exponentially outwards, this scattering occurs more or less near the mirror points. Due to this scattering process, the mirror points move downwards. In a steady state, where particles are injected at constant rate, the density of the electrons below the altitude of injection varies inversely proportional to the air density. Lifetimes of several days to several years are possible, depending on the location of the mirror points. (Author)

Dessler, A. J. and Robert Karplus, "Some Properties of the Van Allen Radiation," Phys. Rev. Letters 4, No. 6, pp. 271-274, 1960

The purposes of this letter are twofold: first, to point out that the results of the observations of the outer zone of the Van Allen radiation belt made with the Explorer IV and Explorer VI satellite systems are inconsistent with the solar injection hypothesis; and second, to show that the electrons released in the decay of cosmic-ray neutron albedo may represent a satisfactory source for the outer zone. (Author)

Dragt, A. J., "Trapped Orbits in a Magnetic Dipole Field," Rev. Geophys. 3, pp, 255-298, 45 refs., 1965

The motion of a trapped charged particle in a dipole magnetic field is reviewed. An extensive discussion is given of the equations of motion in various coordinate systems and of their solution by approximate and analytically exact methods. Wherever possible, approximate solutions are compared with exact solutions obtained by numerical integration. (Author)

Fairfield, D. H., "Trapped Particles in a Distorted Dipole Field," Jour. Geophys. Res. 69, No. 19, pp. 3919-3926, 19 refs., 1964

A dipole magnetic field is analytically compressed and extended to represent a possible effect of the solar wind on the earth's magnetic field on the day and night side of the earth in the earth-sun meridian plane. The first and second adiabatic invariants of particle motion are used to calculate the mirror points of constant energy particles in the compressed and extended fields. The results support and clarify work by previous investigators, showing that shifts in mirror points of particles moving from one field to the other are large at large distances and smaller at lower altitudes. The results are compared to the experimental findings of recent satellites. It is concluded that field distortion may be a major cause of the observed shift in mirror points, but that final resolution of the problem will depend on further determination of the magnetic field on the night side of the earth. (Author)

Gall, Ruth, "Störmer's Inner Allowed Regions and the Radiation Belts," Jour. Phys. Soc. Japan 17, Suppl. A-II, pp. 139-144, 1962

The inner allowed Störmer region is examined and the parameters of particles trapped in this region are presented. The relationship between the Störmer theorem and the injection mechanism for particles trapped is discussed. It is suggested that the mechanism of a particle coming from infinity through the open Störmer pass and undergoing a collision which causes the pass to close is an implausible one. Orbits within the inner allowed region are discussed and the limiting energy for which the adiabatic mirror latitude prevails is determined.

Gall, Ruth, "Motion of Charged Particles in Slowly Varying Fields to the First Order of Approximation," Jour. Geophys. Res. 68, No. 12, pp. 3565-3576, 1963

Following Bogolyubov's and Zubarev's perturbation method, we analyze the motion of a charged particle to the first order of approximation. The general case of motion in a time-dependent nonhomogeneous magnetic field in the presence of an electric field and currents, as well as simpler cases, is considered. Correction terms of the average kinetic energy, the acceleration, and the position of mirror points, as well as a formula for the first adiabatic invariant to $1/\Omega$ order, were obtained. The guiding center's mirror points differ, in all cases, from the points of magnetic reflection of the particle, which contain an oscillatory term and depend on the average phase angle. Only for the case of a static nonhomogeneous field, in the absence of an electric field and currents, the magnetic moment is conserved and all the first-order correction terms vanish. (Author)

Gardner, C. S., "Adiabatic Invariants of Periodic Classical Systems," Phys. Rev. 115, No. 4, pp. 791-794, 1959

Recently there has been renewed interest in adiabatic invariants of simply-periodic classical systems subject to perturbation by slow variation of parameters. In several interesting cases it has been shown that, if the system varies slowly from one steady state to a different steady state, the appropriate adiabatic invariant is constant to an arbitrarily high order in a slowness parameter. It is shown here how these and similar results may be derived by systematic use of a technique of perturbation theory of classical Hamiltonian systems. The method is essentially iteration of the transformation to action and angle variables. (Author)

Hassitt, A., "The Drift Velocity of Trapped Particles," Jour. Geophys. Res. 70, No. 3, p. 535, 1965

The longitudinal drift velocity of a particle trapped in the earth's field is considered. It is shown that there is a relation between drift velocities at different points on any line of force and that the drift velocities of particles with different mirror points are also related. These relations can be used to simplify the calculation of the average effects of the atmosphere. (Author)

Hayakawa, Satio and Haruo Obayashi, "Canonical Formalism of the Motion of a Charged Particle in a Magnetic Field," Nagoya U. -TPPJ-5, N63-15503, February, 1963

The motion of a charged particle in a static magnetic field with axial symmetry is formulated by introducing a set of canonical variables. It is shown to be possible to choose these variables as describing three

modes of motion, the gyration about a line of force, the drift along the line of force, and the azimuthal drift about the symmetry axis. The Hamiltonian expressed in terms of these variables is expanded in power of a small parameter that is of the same order of magnitude as the ratios of the gyration radius to the radii of curvature of a line of force and of a magnetic equipotential line and also to the distance from the axis. The zeroth order Hamiltonian thus obtained describes the motion in the first order orbit theory, whereby the magnetic moment is taken as equal to the action variable of the gyration mode at a line of force at which the kinetic angular momentum vanishes. The mirror point migration is obtained in a higher order approximation. (Author)

Hones, E. W., Jr., "Motions of Charged Particles Trapped in the Earth's Magnetosphere," Jour. Geophys. Res. 68, No. 5, pp. 1209-1219, 26 refs., 1963

Recent measurements by earth satellites provide conclusive evidence that the magnetosphere of the earth is distorted by the solar wind, as has been predicted on theoretical grounds for some time. In the work reported here, motions of charged particles trapped in the distorted magnetosphere were computed by using, as a model of the magnetosphere, the field of a weak magnetic dipole in the presence of a strong magnetic dipole. Drift paths through this field were calculated both for particles whose motion is confined to the magnetic equatorial plane and for particles mirroring at low altitudes. The paths of particles of various energies moving in the magnetic equatorial plane under the combined influences of field gradient-induced drift and field rotation were also calculated. It was found that, in the model used, the field rotation energizes trapped particles on the morning side and de-energizes them on the evening side of the earth. It is suggested that this effect must occur in any realistic model of the distorted magnetosphere and that it may play a role in the accumulation of the energetic particles that constitute the Van Allen zones. (Author)

Hones, E. W., Jr., "Adiabatic Motions of Charged Particles in a Dipole Model of the Magnetosphere," University of Iowa 65-6, 23 p. 1965

The use of the first and second adiabatic invariants of charged particle motion in calculating the trajectories of particles drifting in combined magnetic and electric fields is discussed. Such calculations become particularly simple for a dipole magnetic field if the magnetic lines of force are electric equipotentials. (Author)

Kovalevskiy, A. F., "Characteristics of a Charged Particle Motion in the Geomagnetic Field," Translated from Geomag. Aeron. 3, No. 1, pp. 50-58, NASA TT F-8423, 1963

The motion of a charge in the earth's magnetic trap is considered. A series of characteristics of proton and electron motion are obtained by

numerical solution of charge motion equations. The charge path length between specular points, the particle oscillation period, that of the drift for one period in the latitude direction, the mean drift angular velocity, the rotation period around the earth, the drift's linear velocity and other data are presented. (Author)

Lemaire, J., "Note on Some Consequences of Alfvén's Conditions for Interpreting the Van Allen Zones and Their Movements as well as Distant Azimuthal Currents," University of Liege, Dept. of Astrophysics, AF 61(052)-587 TN-4, (AFCRL-64-226), 1963

The conditions which limit the application of Alfvén's theory of the motion of a charged particle in a magnetic field are discussed. A criterion is found which appears to be satisfied by experimental data and observational data on the Van Allen Belts. This criterion distinguishes the regions of applicability of Alfvén's theory and Störmer theory. Alfvén's theory applies to trapped particles in a magnetic field. The criterion allows one to construct diagrams giving, as a function of energy of various types of particles, the maximum distance at which they remain trapped in the geomagnetic field. The author also shows that taking this condition into account leads to drift velocities and induced currents which should, at large distance, vary as $1/r_e^2$ and $n(r_e)/r_e^2$ respectively where r_e is the distance from the dipole to the point where the line of force crosses the equatorial plane.

Liemohn, Harold, "Radiation Belt Particle Orbits," Boeing Scientific Research Laboratories, D1-82-0116, 56 p., 41 refs., 1961

The first-order theory of radiation belt particle orbits is reviewed. Certain general characteristics of the radiation belts, the exosphere, and the geomagnetic field which are important in orbit calculations are discussed. The equations for charged particle orbits in slowly varying magnetic fields are developed from elementary principles. These results are applied to particle motion in the geomagnetic field. The orbit equations and related parameters are derived for the geomagnetic dipole model. The values of the orbit integrals for the dipole case are given in tabular and graphical form.

McIlwain, C. E., "The Radiation Belts, Natural and Artificial," Science 142, pp. 355-361, 1963

Many characteristics of the radiation belts have been clarified by data obtained by Explorer XV. Spatial distributions of electron and proton intensities are mapped representing conditions observed during the operation of Explorer XV.

Nakada, M. P., J. W. Dungey and W. N. Hess, "Theoretical Studies of Protons in the Outer Radiation Belt," NASA TMX-640-64-110, 1964

The variations in the energy spectra with pitch angle and L of the relatively stable 0.1 to 5 Mev protons in the outer radiation belt have been found to be in good agreement with the results of a model that permits rapid motion of the protons in L space. In this model, the protons violate the third adiabatic invariant of trapped particle motion but do not violate the first two adiabatic invariants. Changes in fluxes with L are not consistent with Liouville's theorem. Both the departure from Liouville's theorem and variations in energy spectra seem to indicate that the source of these protons is at large L. (Author)

Northrop, T. G. and E. Teller, "Stability of the Adiabatic Motion of Charged Particles in the Earth's Field," Phys. Rev. 117, No. 1, pp. 215-225, 1960

The motion of charged particles in a magnetic field such as that of the earth or that of a magnetic mirror machine is discussed. It is shown that during the motion and drift of a relativistic particle not only the magnetic moment but also a longitudinal invariant and an additional flux invariant are adiabatically conserved. These conservation laws lead to retention of the particles in the field. The derivation of the adiabatic invariants leads to a set of equations of motion which describe the average drift of the particles from one force line to the other, and which also describe the changes that occur in the energies and periods associated with the motion. In the absence of scattering, loss of particles from the magnetic field will be due to the violation of the adiabatic laws. (Author)

Northrop, T. G., The Adiabatic Motion of Charged Particles, Interscience Publishers, New York, 109 p., 1963

The author treats in some detail the guiding center theory of motion of charged particles in a magnetic field. The term "guiding center" arises because in a slowly varying field the particle moves approximately in a circle whose center drifts slowly across the lines of force and moves rapidly along the lines. Also, the adiabatic invariants of the motion of charged particles in slowly varying magnetic field are discussed and some applications of adiabatic theory are presented. One application is the description of the motion of particles trapped in the geomagnetic field.

O'Brien, Brian J., "The Trapped-Radiation Zones," Space Physics, ed. D. P. LeGalley and A. Rosen, John Wiley & Sons, New York, p. 505, 111 refs. 1964

This survey article discusses the dynamics of particle motion, adiabatic invariants, the B and L coordinates, the experimental measurements, particle spatial, energy, and angular distributions and mechanisms for generating and losing Van Allen radiation.

Pletnev, V. D., "Density and Intensity Distribution of Charged Particles in a Stationary Geomagnetic Field, Without Considering Particle Interaction," NASA TT F-8829, N64-23044, 1964

The asymptotic method of solving the Boltzmann equation for a low density ionized gas in a strong stationary magnetic field is applied to evaluate the density and intensity distribution of charged particles in the radiation belts of the earth. The method which is based on the expansion of the distribution function for charged particles in inverse powers of the Larmor frequency is extended to the conservation of the invariant of the longitudinal action of the particle in the magnetic field. For this purpose, an additional averaging of the distribution function over the oscillation period of the particle is carried out. Various possible forms of the distribution function together with the corresponding density and intensity distributions of charged particles in the field are considered in these approximations. (Author)

Pletnev, V. D. and G. A. Skuridin, "Motion of a Charged Particle in a Stationary Magnetic Field in the Approximation of Average Drift," Cosmic Research, Vol. 2, No. 1, 1964, Translation, Air Force Systems Command, FTD, Wright-Patterson AFB, Ohio, pp. 74-95, N64-23858, 1964

Consideration is given to the motion of a charged particle through a stationary, nonhomogeneous magnetic field in a drift approximation averaged over a period of oscillation of the particle between magnetic mirrors. The derivation of corresponding equations of motion is based on the Volosov method. It is demonstrated that an approximation of the average drift corresponds to an approximation of the adiabatic invariant of longitudinal action. The rate of deviation of this invariant in the approximation of average drift is found. (Author)

Pletnev, V. D. and G. A. Skuridin, "On the Adiabatic Invariant Motions of a Charged Particle in a Stationary Nonhomogeneous Magnetic Field," NASA TT F-8828, N64-23127, 25 p., 1964

The principles of the classical theory of adiabatic invariants are used to consider the conditions for the conservation of the first, second, and third invariant of the motion of a charged particle in a three-dimensional magnetic system. Such a motion of a particle in a magnetic field is not, strictly speaking, conditionally-periodic. Therefore, in principle, the adiabatic approximation may diverge because the variables in the Hamilton-Jacobi equation cannot be separated. A problem is formulated for evaluating the accuracy of the conservation of the second and third invariants in a stationary magnetic field. (Author)

Ray, Ernest C., "On the Application of Liouville's Theorem to the Intensity of Radiation Trapped in the Geomagnetic Field," State University of Iowa, SUI-59-21, 1959

The classic application of Liouville's theorem to cosmic radiation is reviewed, and simple applications to the case of radiation trapped in the earth's magnetic field are presented. (Author)

Ray, E. C., "On the Theory of Protons Trapped in the Earth's Magnetic Field," Jour. Geophys. Res. 65, No. 4, pp. 1125-1133, 21 refs., 1960

A differential equation of transport is written for protons losing energy in an atmosphere but not scattering. It is solved under the approximation that a proton loses a negligible amount of energy while it drifts once around the earth in longitude. Three cases are treated: the equilibrium solution withinput and loss rates equal; the solution for impulsive injection at t = 0, the intensity then dying away; and the solution for the intensity zero initially, the input mechanism being turned on at t = 0. No numerical work bearing on the geometry of the source function is included. The treatment is an improvement over previous ones in that it adequately treats the particles as moving along their actual trajectories. A detailed comparison with observations over South Africa shows that the altitude dependence of intensity is roughly consistent with the view that the particles seen by the unshielded Geiger tube on 1958ε are protons supplied by a weak source (for example, by decay of albedo neutrons) which are lost to the detector when their energy is reduced below the detection threshold by absorption. (Author)

Swift, D. W., "The Effect of Transverse Electric Fields on the Mirror Points of Charged Particles in the Magnetosphere," Jour. Geophys. Res. 70, No. 11, pp. 2529-2534, 1965

The effect of an electrostatic field on the mirror altitudes of charged particles is calculated under the assumption that the magnetic field lines are equipotentials and that the electric field drift velocities are small compared with the particle velocities. It is found that the electric field on the mirror altitudes of charged particles can be presented as a function of the geocentric distance of the particle in the equatorial plane independent of the explicit form of the electric field. The results of the computation are summarized in two graphs. It is also shown that the presence of a transverse electrostatic field does not affect the longitudinal invariant. (Author)

Vakhnin, V. M., G. A. Skuridin and I. N. Shvachunov, "Motion of Charged Particles in a Magnetic Field with the Consideration of Dissipative Disturbances," Cosmic Research IV, ed. Muller, North Holland, Interscience Publishers, New York, pp. 690-700, 1964

Trajectories of charged particles in a magnetic dipole field are analyzed taking into account the low kinetic energy losses by radiation of electromagnetic waves due to the curvature of the particle's trajectory in the magnetic field. It is shown by a phase plane method that there are critical trajectories for which an arbitrarily small loss of the particle's kinetic energy leads to its trapping in the magnetic field.

The mechanism considered is of interest primarily for the investigation of the problem of the origin and evolution of the earth's radiation belts. (Author)

Vakhnin, V. M. and I. N. Shvachunov, "The Possibility of Capturing Charged Particles in the Field of a Magnetic Dipole If Energy is Lost as a Result of Emission," Cosmic Res., Vol. 2, No. 5, 4 Nov. 1964, pp. 191-199, Air Force Systems Command, Wright-Patterson AFB, Ohio, FTD, N65-16401, 1964

The investigation of the possibility of capturing charged particles in the field of a magnetic dipole which was carried out earlier for two-dimensional motion is extended to the case of an arbitrary three-dimensional particle motion. Use is made of a method of phase trajectories in a four-dimensional phase space. It is demonstrated that the "critical trajectories" and the possibility of capture exist in three-dimensional motion as well. (Author)

Wentworth, R. C., W. M. MacDonald and S. F. Singer, "Lifetimes of Trapped Radiation Belt Particles Determined by Coulomb Scattering," Phys. Fluids 2, No. 5, pp. 499-509, 1959

Once introduced into captive orbits, protons and electrons should be strictly trapped in the earth's dipole magnetic field. However, various mechanisms exist which limit their lifetimes, such as collisions with atoms and ions in the earth's outer atmosphere, charge exchange, and scattering by hydromagnetic waves. This paper considers only the effect of the scattering of these particles by the ionized hydrogen and electron components of the outer atmosphere. However, the effect of scattering from neutral atoms can be qualitatively taken into account by using the radius of the atom in place of the Debye shielding length in the scattering formulas. The Fokker-Planck equation has been used to derive an expression for the change in the distribution function due to small-angle, single-particle Coulomb collisions. Upper lifetime limits, as determined by this mechanism, of both protons and electrons are derived as functions of their initial energies. (Author)

RING CURRENTS IN THE MAGNETOSPHERE

Akasofu, S.-I. and W. C. Lin, "The Magnetic Moment of Model Ring Current Belts and the Cutoff Rigidity of Solar Protons," Jour. Geophys. Res. 68, No. 4, pp. 973-977, 13 refs., 1963

The magnetic moment M_R of the ring current is calculated for model ring current belts, together with their magnetic fields along an equatorial radius. A graph shows the relation between the ratio M_R/M_E (M_E = the magnetic moment of the earth) and the intensity ΔH of the ring current field at the equator on the earth's surface. It gives possible ranges of the ratio M_R/M_E for observed values of ΔH and approximate upper limits of both M_R/M_E and ΔH for each belt. On the basis of diagram, the entry of low-energy solar protons is discussed, and it is shown that the ring current alone cannot produce the drastic reductions of apparent cutoff rigidity of solar protons observed by detectors carried by balloons and satellites. (Author)

Akasofu, S.-I. and J. C. Cain, "The Magnetic Field of the Radiation Belts," NASA TND-1762, 8 p., 1963

The magnetic fields produced by various types of belts of trapped particles are presented in both tabular and graphical forms.

Akasofu, S.-I. and Sydney Chapman, "The Ring Current, Geomagnetic Disturbance, and the Van Allen Radiation Belts," Jour. Geophys. Res. 66, No. 5, pp. 1321-1350, 32 refs., 1961

The large decrease in the horizontal component of the earth's field during the main phase of magnetic storms has been ascribed to the formation or enhnacement of a geomagnetic ring current. In this paper we discuss the motions of particles trapped in the earth's dipole field and the resulting ring current. These calculations deal only with a steady state, though during storms the state is changing. The general equations for the current intensity, to obtain the total current and the magnetic field at the earth's center, are applied to the outer radiation belt (V_2) and to a special "model" belt V_3. This V_3 belt has a particular type of pitch-angle distribution and a number-intensity distribution of Gaussian type along an equatorial radius. The results are considered in connection with magnetic records for several storms and with satellite data. It is inferred that, during magnetic disturbance, protons of energy of the order of a few hundred kev are intermittently captured between 5 and 8 earth radii and that they produce a transient belt V_3. The variety of development of the ring current from one storm to another may be connected with irregularities in the distribution of particles in the solar stream, which may contain tangled magnetic fields. (Author)

Akasofu, S.-I. and J. C. Cain, "The Magnetic Field of the Quiet-Time Proton Belt," NASA TN D-1674, 1963

The distortion of the earth's magnetic field produced by the proton belt is discussed. The magnetic field is calculated numerically, to a first approximation, for an analogous model belt, in a steady state. In the equatorial plane, at the earth's surface, it is estimated that the magnetic field produced by this belt is of order 38 gammas; it is directed southward. The maximum field reduction is of the order of 72 gammas at 4.1 earth radii; this is 15.5 per cent of the dipole field intensity at this point. Beyond 6.7 earth radii, the belt increases the earth's field. (Author)

Apel, J. R., S. F. Singer and R. C. Wentworth, "Effects of Trapped Particles on the Geomagnetic Field," Advances in Geophysics 9, pp. 131-189, Academic Press, New York, 1962

The trapped particle motion in a dipole field is discussed including the magnetic moment and the drift velocity. Approximate values for the magnetic fields of the trapped particles are calculated. The perturbation of the magnetic field due to radiation belt currents is calculated and the distribution of trapped particles is discussed. Liouville's theorem is applied to the geomagnetic field for the purpose of calculating particle distributions in the field.

Ben'kova, N. P. and L. O. Iyurmina, "Magnetic Field of the Equatorial Current" Geomagnetism and Aeronomy 2, No. 4, 1962, NASA TT F-8303, 13 p., 1962

The latitude distribution of the ring current's magnetic field is computed upon admission that the generatrix of the current surface has the shape of a dipole field line of force, and that the density of the current is in various ways dependent on the polar distance Ψ. The best concordance between the computed component X and the latitude distribution of the D_{st}-variation of the magnetic field was obtained for a ring radius $a = 9R_E$ and a current density $j = j_0 (b + \cos^2 \Psi)$. The value of the ring current's magnetic moment $M = (4.5) \cdot 10^{25}$ CGSM agrees well with the data of other authors. (Author)

Cahill, L. J.,"The Geomagnetic Field," Space Physics, ed. D. P. LeGalley and A. Rosen, John Wiley & Sons, New York, pp. 301-349, 66 refs., 1964

This is a survey article on the geomagnetic field. The spherical harmonic expansion of the field is discussed. Variations of the field and their causes are also discussed. The search for the ring current is outlined and the interaction between the solar plasma stream and the magnetosphere is discussed. A good list of references on these subjects is included.

Chapman, S. and V. C. A. Ferraro, "A New Theory of Magnetic Storms," Terr. Mag. and Atm. Elec. 36, pp. 171-186, 1931

The interaction between the solar plasma stream and the geomagnetic field is discussed. The geomagnetic field shields the earth from the stream of particles and the conducting stream confines the field in the sunward direction. A net ring current in the westward direction is predicted.

Chapman, Sydney, Solar Plasma, Geomagnetism and Aurora, Gordon and Breach, New York, 141 p., 1964

The mutual influence of the solar gas and the geomagnetic field and the magnetosphere shape are discussed. Several models of the ring current and their fields are discussed.

Dessler, A. J., W. B. Hanson and E. N. Parker, "A Mechanism to Establish the Magnetic Storm Ring Current," Jour. Phys. Soc. Japan 17, Suppl. A-1, pp. 178-182, 1962

It is shown how hydromagnetic waves generated by the impact of solar plasma on the geomagnetic field may form shock waves in the magnetosphere and provide a means of creating the geomagnetic storm, main-phase, diamagnetic ring current. These shock waves should develop on the night side of the earth and heat the ambient protons (which constitute the normal protonosphere) to approximately the hydromagnetic-wave velocity (of the order of 500 km/sec). The transfer of hydromagnetic wave energy to the protons stresses the geomagnetic field and produces the geomagnetic-storm main phase; i.e., the kilovolt-energy protons form a diamagnetic current. The bombardment of the upper atmosphere by energetic hydrogen atoms from the decaying ring current and the possible change in the decay time-constant of the ring current through the sunspot cycle are discussed. (Author)

Kellogg, P. J. and J. R. Winckler, "Cosmic Ray Evidence for a Ring Current," Jour. Geophys. Res. 66, No. 12, pp. 3991-4001, 25 refs., 1961

Many observations show that low rigidity protons from solar flares are permitted entry at Minneapolis only during the main phase of magnetic storms. The measured energy is much below the normal Störmer cutoff at that time. This paper develops the idea that a ring current responsible for the main storm field reduces the Störmer cosmic-ray cutoffs. The model of the ring chosen is actually an azimuthal current on the surface of a sphere with current intensity proportional to sin θ where θ = colatitude. It is shown that this mathematical form permits great simplicity in the analysis and leads to essentially the same result as a diffuse ring corresponding to the actual trapped radiation. The magnetic moment of the ring required to produce the cutoff change can be provided by reasonable intensities of very low energy trapped radiation. It is shown that the cosmic-ray data

permit one to evaluate both the moment (M') and radius (R) of the ring, whereas the surface magnetic measurements determine only the quantity M'/R^3. Since observation shows that the cosmic-ray cutoffs return to normal during the main phase, it must be assumed that the ring shrinks inward so that the surface field is maintained negative. Cosmic-ray evidence concerning the presence of a permanent ring current is discussed. Such a ring is measured directly by satellites during quiet times. (Author)

Kozlowski, M. F., "Guiding-Center Approximation in the Diamagnetic Ring Current," Jour. Geophys. Res. 68, No. 15, pp. 4421-4428, 1963

Guiding-center approximation for protons in the diamagnetic ring current is valid when two known conditions are satisfied. The critical energies, magnetic rigidities, and pitch angles in the geomagnetic field and the field of the ring current are studied, and the results are applied, as an example, to a model ring current belt proposed by Akasofu and Chapman. It is found that protons with energies 20-40 kev are most likely to be responsible for the belt. The lifetime of these protons in the ring current belt is estimated at 10 days, as observed on the magnetograms. The pp pulsations may, as it seems, be the cause of magnetic scattering of the ring current. This is suggested on the basis of the coincidence of commencements of pp pulsations observed by Troitskaya and the quicker increase of the H force during the main phase at equatorial magnetic stations. (Author)

Ray, E. C., "Effects of a Ring Current on Cosmic Radiation," Phys. Rev. 101, No. 3, pp. 1142-1148, 15 refs., 1956

A theoretical analysis of the effect of an equatorial ring current on the latitude variation of the primary cosmic radiation has been carried out. It has been found that a ring current of the size suggested by Schmidt should lead to observable effects on the latitude variation. In particular, if a ring current of radius equal to 7.5 earth radii and current strength sufficient to produce a field of 100γ at the earth's equator exists, then the knee in the latitude variation is a feature of the rigidity cut-off curve rather than of the primary spectrum. The primary spectrum obtained with the use of geomagnetic theory which includes a ring current is satisfactorily fitted with a function of the form $J = 0.29\ E^{-0.9}$ $(cm^2\ sec\ sterad)^{-1}$, where E is the total energy of a primary particle. Certain features of time variations of the cosmic-ray intensity apparently disagree with the theory. (Author)

Ray, E. C., "Effects of a Ring Current on Cosmic Radiation. Impact Zones," Phys. Rev. 104, No. 5, pp. 1459-1462, 1956

An investigation of the effects of a ring current on the "0900" (geomagnetic local time) impact zone of flare-associated cosmic-ray intensity increases has been carried out using 55 trajectories calculated on an automatic computer. The particles considered have rigidities of 2 Bv, 6 Bv, and 10 Bv, and arrive at the earth from the vertical direction. Reasonable ring currents shift the longitude of impact by as much as half an hour from that predicted by the dipole theory. The shift may be in either direction, depending on the exact ring parameters chosen. Experimental data so far published are not sufficiently accurate to test the theory. Because of the finite width of observed impact zones together with the rather small shift predicted here, the experimental test is inherently difficult. (Author)

Ray, E. C., "The Terrestrial Ring Current," Jour. Geophys. Res., 69, No. 21, pp. 4421-4427, 1964

Several people have computed numerically the magnetic field caused by an axially symmetric body of plasma imbedded in a dipole magnetic field. In the present paper we derive an approximate formula for this magnetic field, without first choosing a particular functional form for the plasma density. This has the consequence that we can easily discuss any particular case without recourse to a computer, whereas previous treatments resulted in a tabulation of an answer for a particular case only, and new cases required new computer runs. The method used avoids the usual fine net required by the singularity in the integrand. We achieve this by constructing a new quadrature formula which treats this singularity exactly. The then permitted coarse net makes possible an algebraic treatment rather than a numerical one. (Author)

Treiman, S. B., "Effect of Equatorial Ring Current on Cosmic-Ray Intensity," Phys. Rev. 89, No. 1, pp. 130-133, 9 refs., 1953

The equatorial ring current postulated by Chapman and Ferraro to explain the main phase of terrestrial magnetic storms is analyzed with respect to its effect on the intensity of the cosmic radiation. For mathematical convenience, the ring current is replaced by a current sheet located on the surface of a sphere concentric with the earth, in accordance with a suggestion due to Chapman. A simple expression is then obtained relating the variations in magnetic field at the equator with the corresponding variations to be expected in the intensity of cosmic radiation measured by an arbitrary detector located at any latitude and atmospheric depth. (Author)

Vestine, E. H., "Note on Low-Level Geomagnetic Ring-Current Effects," Jour. Geophys. Res. 68, pp. 4897-4907, 51 refs., 1963

Various measurements of the intensity of radiation within the inner Van Allen belt have indicated little possibility that the equatorial magnetic field of the belt should exceed 0.5γ. The 12-year means of geomagnetic disturbance data show an equatorial latitude variation, which could arise from a transient equatorial ring current at a height within the outer reaches of the inner belt. This small transient equatorial ring current may be introduced to suitable equatorial heights by downward expansion of a higher ring current present during magnetic storms. This possibility would be susceptible of experimental check. Another possibility is increased westward current flow within the equatorial ionosphere or enhanced compression of the equatorial magnetosphere during storm days.

SPACE RADIATION SHIELDING USING MAGNETIC AND ELECTRIC FIELDS

Benedikt, E. T., "Cosmic Radiation Shielding of Space Vehicles by Axially Symmetric Electric Currents," North American Aviation, Inc., SID 64-387, AD 459-262, 1964

This report should be useful for the design of an electromagnetic system capable of affording a pre-established amount of shielding from cosmic radiation. To fulfil this requirement, an (implicit) equation of the boundaries of the zones inaccessible to cosmic rays of a given energy impinging from a given direction is derived for the case where the system of electric currents, and hence for the magnetic field generated thereby has cylindrical symmetry. (Author)

Bernert, R. C. and Z. J. J. Stekly, "Systems Analysis of Superconducting Magnets for Space Radiation Shielding," AVCO, Contract No. NAS8-5278, 1964

Active shielding systems using superconducting coils are compared with solid spherical passive shields on a weight versus dose rate basis. The discussion given includes the consideration of magnetic field geometry; the calculation of the mass of superconducting coil systems comprised of superconductor, structure and cryogenic environment; the method of primary proton dose calculation; the secondary dose problem; and the results of the weight and shielding calculations for different shielding levels and shielded volumes. (Author)

Bernert, R. E., "Design of a Mars Class Radiation Shield Using a Superconducting Magnet," AVCO, Contract No. NAS8-5278, 1964

This study establishes the design feasibility of a space radiation protection system using a superconducting magnet system which might be applicable to early Mars Exploration Systems. It includes the major design and operational characteristics of such a system as well as a discussion of the economics of this concept in relation to passive shielding. (Author)

Bhattacharjie, A. and I. Michael, "Mass and Magnetic Dipole Shielding Against Electrons of the Artificial Radiation Belt," AIAA Jour. 2, No. 12, pp. 2198-2201, 1964

Computations of magnetic shielding system masses required for protection against electrons of various energies have been performed. We have also obtained a comparison of the required shielding masses for a space vehicle traversing circular orbits through the anomaly in the artificial radiation belt (ARB) at altitudes of 200, 400, 600, and 800 km and inclined at 30° to the earth's equatorial plane: first with a magnetic superconducting

solenoidal shielding system approximated by a point dipole and then with a two-layer composite material shielding system consisting of an outer layer of aluminum and an inner layer of lead. The aluminum thickness equaled the practical range of 10-Mev electrons, and the lead was used to attenuate the bremsstrahlung to specified skin dose rates. The averaged electron flux in ARB, used in estimating dose, was computed to be sufficiently accurate for missions not shorter than 100 hr and more accurate for longer missions. The material shielding mass, primarily designed for protection when appreciable bremsstrahlung occur, was at best (no lead) an order of magnitude larger than that of the magnetic shielding system. The mass of the cryogenic system was neglected, being a fraction of the combined mass of the solenoid and support structure.

Brown, G. V., "Magnetic Radiation Shielding," Proceedings of Conference on High Magnetic Fields, (Kolm, ed.), MIT Press, pp. 370-378, 1962

The shielding of space vehicles from solar flares and cosmic ray primary radiation by magnetic fields is considered. Axially symmetric fields such as the dipole field, the field of a circular loop, finite and infinite solenoids and a deformed toroidal geometrics are discussed in terms of their shielding effectiveness. A comparison is made of the shielding masses required for passive shielding and active shielding using the various field configurations. Also the unusual requirements of magnetic shields such as field strength, stored energy and structural strength are stated.

Cladis, J. B., et al., "Feasibility of Magnetic Orbital Shielding System," Lockheed Missiles and Space Company, Technical Report 8-94-64-2, 236 p. 17 refs., 1964

The shielding of spacecraft against bomb-injected electrons with magnetic deflection systems is investigated. The shielding by a dipole and the finite loop are discussed using the Störmer theory. The shielding effectiveness of loops comparable in size to a space vehicle is investigated by computing large numbers of electron trajectories assuming certain incident fluxes and observing the number and positions of the intersections of trajectories with a fictitious spacecraft surface. The advantages and disadvantages of certain multiloop magnet configurations are considered. The effects of high magnetic fields on various electronic components are discussed. The results of an experimental program to design, construct, and operate a superconducting 1.2×10^5 ampere-turn coil six feet in diameter are also presented.

Dow, N. F., S. P. Shen and J. F. Heyda, "Evaluation of Space Vehicle Shielding," General Electric, R62SD31, 124 p., 1962

A general method of evaluating the efficiency of space vehicle shielding is developed and used to compare various active and passive systems for protection against ionizing radiation. Available permanent magnets are found useless for active shielding, and combined active-passive systems in general are determined to be inefficient. On the other hand, evaluations show that active electrostatic shielding may have possibilities for weight savings if electrical conditions (presently unknown) are favorable therefor in space. Further, a positive potential improvement is calculated for an active shielding system which utilizes superconducting Nb_3Sn to provide a confined magnetic flux to deflect incident charged particles; this potential points toward substantial reductions in shield weight for the protection of large vehicles from highly energetic particles. (Author)

Edmonson, N., C. D. Verwers and F. L. Gibbons, "Shielding of Space Vehicles by Magnetic Fields," Proc. of the Symposium on the Protection Against Radiation Hazards in Space, Gatlinburg, Tennessee, November 5-7, 1962, AEC TID 7652, 1962

A program has been initiated at General Dynamics/Fort Worth to study various aspects of magnetic shielding of space vehicles. In one phase of the program, a procedure has been formulated and coded for the IBM-7090 computer for rapidly computing the field of an optimized superconducting solenoid. In another phase, samples of NbZr wire have been irradiated with neutral particles from two sources. Preliminary results are now available. Irradiation with 10^{11} neutrons per cm^2 from the D-T reaction showed no change in the critical current versus magnetic field curve. Irradiation with 10^{16} neutrons (>2.9 Mev) per cm^2 showed a slight downward shift in the critical current. It is difficult to say whether this shift was due to the irradiation or due to the environment during the irradiation. (Author)

Hawkins, S. R., "A Six-Foot Laboratory Superconducting Magnet System for Magnetic Orbital Satellite Shielding," International Advances in Cryogenic Engineering, Plenum Press, pp. 124-136, AD-619 801 Div. 20/6, 1965

As a part of a feasibility study, a program was undertaken to design, construct, and test a laboratory superconducting magnet system which, as far as possible, is compatible with the shielding requirements of the Agena vehicle in the artificial radiation belt.

Kash, Sidney W. and R. F. Trooper, "Active Shielding for Manned Spacecraft," Astronautics, pp. 68-75, 36 refs., September 1962

The charged particle radiation environment is discussed and the principles of magnetic shielding are outlined using Störmer theory.

Levy, R. H., "Radiation Shielding of Space Vehicles by Means of Superconducting Coils," AVCO RR 106, 1961

The general problem of shielding the occupants of manned space vehicles from various radiations likely to be encountered in space flight is discussed, and various published papers on the subject are briefly reviewed. The review indicates the importance of the problem and the interest that would attach to a radical solution. One possibility is shielding by the permanent magnetic field of a superconducting coil. A detailed analysis is made of the shielding that could be provided by such a coil and a preliminary estimate of the weight of such a device is made paying particular attention to the weight of the structure required to support the coil. A comparison is made of the weights calculated in this way with the weight of the spherical H_2O shield which would give comparable protection.

Levy, R. H., "The Prospects for Active Shielding," AVCO, AMP-94, 1962

Recent work on active shielding is reviewed. Electrostatic shielding is discussed and appears unattractive. Magnetic shielding is discussed and compared with material (passive) shielding. It is found that for sufficiently large sizes magnetic shielding will always be superior, but that the sizes involved are extremely large. The possibility of shielding a spacecraft by blowing a hole in the interplanetary field (along which the protons move) with an atomic bomb is mentioned, but it appears that such a shield would violate Liouville's theorem.

Levy, R. H. and G. S. Janes, "Plasma Radiation Shielding," AVCO, RR 192, 10 pp., 1964

A new scheme is suggested which is intended to make possible the maintenance of a space vehicle at a potential of several hundred million volts above its surroundings. Such a vehicle would be electrostatically shielded against high energy incident protons, but would attract electrons from the interplanetary plasma. The key to the maintenance of the potential is the control of these electrons by a magnetic field. The magnetic field strength required to control these electrons is far less than the strength required (as in a pure magnetic shield) to control energetic protons. As a result, engineering estimates of the weight of this device (assuming superconductors) show that it offers the possibility of a substantially increased shielded volume per unit weight.

Levy, R. H. and G. S. Janes, "The Electron Plasma - Experiment Theory and Applications," AVCO, AMP 160, 12 pp., 1965

The basic concepts involved in the production and control of pure electron and electron rich plasmas are reviewed, with particular reference to the different geometries in which equilibrium may be achieved. An inductive method of establishing arbitrary equilibrium profiles is described. Recent theoretical work on the stability of some particularly simple equilibria is then discussed. Instabilities considered are: 1) The so-called diocotron (or slipping stream) instability, this instability (whose importance in magnetron work is well understood) is related to the Kelvin-Helmholtz instability in fluid mechanics; 2) A new mode involving spontaneous coherent radiation into space as a result of bunching. This effect can be described as the "flexible antenna instability". Both these instabilities are considered for low density electron beams (that is, $\omega_p << \omega_c$). Two experiments are discussed. The object of the first is to produce a stable electron plasma in a simple geometry. The second is designed to test the practicability of the inductive charging scheme. A brief review of selected applications of the electron plasma is also given; these include space radiation shielding and certain high voltage laboratory devices.

Norwood, J. M., "The Combination of Active and Passive Shielding," Proceedings of the Symposium on the Protection Against Radiation Hazards in Space, Gatlinburg, Tennessee, November 5-7, 1962

It is conceivable that improved shielding of space vehicles against high-energy charged-particle radiation can be obtained by combining active and passive shielding. Methods of shielding calculations and some preliminary observations pertaining to active-passive shielding are given. An analysis based on the field of a magnetic dipole indicates that weight savings in bulk shielding can be accomplished. (Author)

Norwood, J. M. and F. L. Gibbons, "Studies of Magnetic Shielding and Superconductivity," General Dynamics Report ERR-FW-210, (AD-423178), 1963

The theoretical portion of this report deals with the shielding against cosmic ray particles using the magnetic field of a finite loop. The author questions the neglect of the dimensions (cross sectional) of the conductor in obtaining the expression for the vector potential which is used to determine the shielded region. By considering a coil of finite dimensions he obtains an expression for the vector potential which is quite complicated. The effect of the new vector potential on the dimensions or the effectiveness of the shielded region were not included.

Prescott, A. D., E. W. Urban and R. D. Shelton, "The Application of the Liouville Theorem to Magnetic Shielding Problems," Proc. of Symposium on Protection Against Radiation Hazards in Space, Gatlinburg, Tennessee, October, 1964

The Liouville theorem and the Störmer theory of allowed and forbidden regions are used to obtain charged particle distributions and flux ratios for a static magnetic dipole field. The allowed and forbidden regions for magnetic quadrupole fields, octopole fields, and fields due to double current loops are presented.

Tooper, R. F. and W. O. Davies, "Electromagnetic Shielding of Space Vehicles," IAS Paper No. 62-156, 30 pp., 32 refs., June, 1962

The shielding of space vehicles by dipole-like magnetic fields using superconducting coils has been considered. Magnetic shielding appears to require less payload capability than passive (bulk) shielding for long missions and high energy particles. The energy distributions of charged particles in space are briefly summarized. The shielded regions for charges moving in a dipole field are discussed. Protons of energy less than 866 Mev are completely shielded and those of energy less than 8.1 Bev are partially shielded by a dipole of moment 3×10^{11} gauss cm^3 over the equator of a sphere of diameter 2 meters; shielding is less effective away from the equatorial plane. Particle trajectories have been calculated to determine shielding effectiveness in the partially shielded regions. Design parameters are given for two sample niobium-tin solenoids. The first has a magnetic moment of 3×10^{11} gauss cm^3 and weighs 2450 lb. (exclusive of the cryogenic system). The second has a magnetic moment of 3×10^{12} gauss cm^3, weighs 4750 lb., and gives a basic radius for the shielded region of 9 meters for 500 Mev protons. (Author)

Tooper, R. F., "Electromagnetic Shielding Feasibility Study," Wright-Patterson AFB, Ohio, Rpt Nr ASD-TDR-63-194, 143 pp., 100 refs., 1963

This report discussed the shielding of personnel against charged particles in space using electric or magnetic fields. The energy distribution and other characteristics of charged particles in space are summarized. The operation and stability of an electrostatic shield (two concentric charged conducting spheres) for protection against 1-Mev electrons and 500-Mev protons is discussed. Shielded regions for charges in a magnetic dipole field are discussed. A method is given for calculating trajectories of particles incident on a magnetic dipole in a parallel beam, with sample trajectories illustrated. The vector potential of a cylindrical solenoid is used to get the shielded region for $L/R = 1.00$, $R/C_{st} = 0.40$. The mass of conductors and structure of superconducting solenoids are calculated in terms of the geometry and dipole moment. A nonoptimum sample has a magnetic moment 5.66×10^{12} gauss cm^3, radius and length 4 meters, weighs 417,000 lb.,

and protects ~50 meters^3 from 1-Bev protons. A single-turn magnetic shield could be made 1/10 the mass of a comparable passive shield for 1-Bev protons. Structural considerations and preliminary shielded volume studies indicate that further decrease in mass could be obtained using an optimized cylindrical solenoid. Recommendations for future work emphasize further studies of cylindrical solenoids and other current configurations. (Author)

Urban, E. W., "Charged Particle Motion in Axially Symmetric Magnetic Fields," Masters Thesis, University of Alabama, 1963

The Störmer theory of allowed and forbidden regions for charged particle motion in axially symmetric magnetic fields is reviewed and applied to three new magnetic configuration--the magnetic quadrupole, a system of two parallel circular loops with the currents in the same direction, and a similar system with currents opposing. Interesting forbidden regions, analogous to those obtained by others for the dipole and single current loop, are found and discussed. A useful mathematical method, based on the existence of saddle points in a potential function analog, is developed and applied to the determination of system parameter values which give optimum shielding.

White, Elmer, "Technique for Calculating Trajectories of Singly Charged Particles in a Static Magnetic Field for Shielding Purposes," Air Force, Aeronautical Syst. Div., TDR-63-72, AD406-384, 1963

The interactions between a charged particle and an externally applied static magnetic field are reviewed. The elementary effects that involve the introduction of an energetic charged particle into a magnetic field are discussed. Equations are derived for the magnetic flux density and for calculating the trajectories of singly charged particles. Also discussed are the applications of these equations and the boundary conditions. These equations are then adapted to the FORTRAN program. The use of the FORTRAN program and the method of data input are explained. Sample problem data, a printout of the program deck, and printouts of the solutions to the problems are also presented. (Author)

Zaytsev, V., "Magnetic Armor Protects Against Cosmic Showers," Translation, Air Force Systems Command, FTD-TT 63-760, 9 pp., 1963

A nontechnical discussion of the magnetic shielding of space vehicles from cosmic radiation is given.

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13. ABSTRACT

This annotated bibliography on the theory of charged particle motion in magnetic fields and the shielding against charged particle radiation using magnetic fields is divided into five sections: 1) general references on charged particle motion and cosmic rays, 2) motion of untrapped particles in magnetic fields, 3) motion of trapped particles in magnetic fields, 4) ring currents in the magnetosphere and 5) space radiation shielding using magnetic and electric fields. It should be helpful to those interested in the interaction of cosmic rays and energetic solar particles with the geomagnetic field and those interested in the active methods of shielding against space radiation.

14. KEY WORDS

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